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SYNCHROTRON RADIATION LEAD SHIELDING OF THE VACUUM CHAMBERS FOR LEP

by

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Summary

The high linear power density and the energetic photon spectrum in LEP impose a complete radiation shield around the vacuum chamber. The absorption and scattering of the photons in the vacuum chamber has been studied with the use of the Monte Carlo shower program EGS in view of defining the lead shielding required for acceptable dose levels. To avoid the excessive production of ozone or of corrosive products in the air surrounding the vacuum chamber it is proposed to apply the lead shield directly onto the aluminium profile. In this way the cooling circuits of the vacuum chamber can cool the lead shield which will later be necessary at increased LEP energies. Different methods of bonding the lead to the aluminium have been studied and have resulted in a cladding process using a tin-lead solder joint. This method has been applied to aluminium tubes of up to 12 m length and to full size prototype vacuum chambers.

Introduction

Early in the design of LEP¹ the importance of synchrotron radiation shielding has been recognised because of the high linear power density of up to several kW/m and the energetic photon spectrum extending to energies in the MeV range. Heating of the vacuum chamber, radiation damage to machine elements and the formation of ozone and nitrogen oxides in the air leading to corrosion of machine components and health hazards for personnel have been considered. These and related problems have been studied previously for the high energy e^+e^- storage rings PEP and EPIC.^{2,3,4} The vacuum chamber design for LEP follows the concept of SPEAR, PETRA and PEP with an extruded aluminium profile incorporating the beam channel, a pump channel and 3 water cooling channels as shown in figures 1 and 2. Due to the the low glancing angle of incidence of the synchrotron radiation on the vacuum chamber (about 6 mrad) the attenuation along the direct photon path traversing the 5mm thick wall is of the order of 10^{-8} , even at the highest photon energies. The radiation which can penetrate the wall must undergo at least one scattering event (mostly Compton scattering), and will subsequently traverse the wall under a steep angle with a low probability for a further interaction. About 60% of the primary synchrotron radiation power escapes from the vacuum chamber in this way and represents a diffuse radiation source. In order to reduce this radiation level outside the beam pipe, additional shielding has to be provided. For LEP the solution adopted consists of a lead shield directly clad onto the aluminium profile. This solution has been retained because it avoids exposure of air to the otherwise high radiation level immediately outside the beam pipe. Furthermore, at the later stages of LEP exploitation with an expected synchrotron radiation power in excess of 2 kW/m, the shielding elements will require cooling which can easily be obtained by the existing cooling system of the beam pipe. The dose to the most exposed machine components must be limited by a continuous radiation shield of between 3-8 mm of lead all around the beam pipe.⁵

Shielding computations

A computer program has been written for use with the electromagnetic shower program EGS,⁶ approximating the elliptic beam channel by a rectangular duct which

Figure 1: Cross section of bending magnet vacuum chamber showing the elliptic beam channel, the rectangular pump channel and 3 cooling channels. The radiation shield consists of 4 extruded lead profiles of 3 to 8 mm thickness.

Figure 2: Cross section of the quadrupole magnet vacuum chamber with 2 cooling channels. The radiation shield consists of 2 identical extruded lead profiles of 6 to 8 mm thickness.

is surrounded by a lead shield. To take account of the synchrotron radiation the energy of the incident photons is sampled over the spectrum. The results are summarised in figures 3 and 4. The nominal lead shield for the bending magnet vacuum chambers in LEP consist in a 3 mm thick layer on top and bottom, and 8 mm thick layer on the vertical surfaces. This difference in shielding thickness has been chosen as a compromise between shielding and the constraint of reducing the gap height of the dipole magnets.⁷ Inspection of figure 3 shows that in the energy range from about 50 GeV onwards, the synchrotron radiation is absorbed about half and half in the aluminium and in the lead shield of the chamber. The fraction absorbed locally in the region of the primary impact of the radiation is close to 40% in this energy range and explains the design of the main cooling channel. The radiation escaping from the vacuum chamber into the surrounding magnets and the machine tunnel is shown in figure 4 for different shielding configurations. The nude chamber is very transparent to synchrotron radiation even at the lowest operating energies of LEP. A uniform shield of 3 mm thickness results in a strong attenuation up to about 50 to 60 GeV beam energy. The addition of lead to the lateral, vertical chamber surfaces reduces the scattered, escaping radiation by a further factor of about 2. An increase from 3 to 4 mm on the horizontal surfaces has

Figure 3: The fraction of synchrotron radiation absorbed in the LEP vacuum chamber and the lead shield as a function of beam energy, a) in the region of the primary impact of the radiation, b) the total fraction absorbed in the aluminium profile, c) the fraction absorbed in the 3 to 8 mm lead shield.

Figure 4: The fraction of synchrotron radiation power escaping from the chamber as a function of the beam energy : a) nude chamber, b) 3 mm shield, c) lead shield of 3 mm on horizontal, 8 mm on vertical surfaces, d) same as c) but with 4 mm lead shield on horizontal surfaces.

not been considered of interest in the gap of the magnet. Of particular concern are vacuum chamber components, not directly exposed to synchrotron radiation, such as vacuum bellows and valves with locally increased aperture. The longitudinal distribution of the absorbed radiation as a function of the distance from the point of impact, shown in

Fig. 5 requires that short elements like bellows, beam position monitors or valves have to be shielded as completely as the adjacent vacuum chamber.

The lead coating process

A detailed analysis of handling, cleaning and welding of precoated aluminium profiles has resulted in the conclusion to consider the lead coating as the last step in the fabrication sequence, following the completed assembly and leak checking of the chamber. The two profiles which have to be coated are those of the bending magnet chambers with 11.7 m unit length and a cross-section as shown in figure 1 and the quadrupole magnet chambers with a length about 3.5 m and a cross-section as shown in figure 2. The sequence of lead coating starts with galvanic tinning of the outside of the vacuum chamber with about 20 μm thickness. Subsequently, the extruded and tinned lead profiles are fitted around the vacuum chamber with the addition of a film of soldering flux. The entire system is then heated to about 210°C where the eutectic phase of the tin-lead system provides the soldering joint. During this process sufficient external pressure has to be applied to ensure the proper mating of the lead profiles with the aluminium surface. The temperature is maintained for about 5 to 10 minutes, long enough to guarantee that the complete 12 m long chamber has reached an even temperature. Subsequently the temperature is reduced and the external pressure released when below the solidification point of the tin-lead solder at 183°C. The bonding relies on the formation of a eutectic phase of tin-lead by diffusion of the two constituents at a temperature slightly above 200°C, i.e. below the individual melting points of either tin or lead. A particular reason for choosing the method described has been that using the tin-lead eutectic to provide the joint results in a bonding which withstands the foreseen vacuum bakeout temperature of 150°C. At the same time it preserves the mechanical strength of the aluminium alloy which would be reduced by even a short exposure to temperatures above 220°C. To guarantee good adherence of the lead a temperature resistant tin coating of the aluminium is of primary importance. This can be achieved by a conventional galvanic tinning method developed for aluminium bus bars or similar electric components.⁸ Nevertheless, a certain difficulty has been experienced of obtaining from industry the specified quality of tin coating on the 12 m long vacuum chambers, mainly because of their size, which requires special installations.

To achieve a temperature resistant tin coating a special preparation of the aluminium and a particular build-up of the galvanic layer has been shown to be necessary. Good results can be obtained with tinning which starts with a chemically deposited sublayer of zinc or bronze, providing adherence to the aluminium and protecting it from oxidation. Next, a nickel coat of a few μm must be applied to act as a diffusion barrier during the subsequent soldering process. The final tin layer of about 20 μm thickness must have good soldering characteristics and must not contain organic brighteners.

Since the coating takes place on the finished chambers, end flanges, lateral outlets and water connections have to be left out when fitting the lead profiles around the chamber. For the shielding of the chamber extremities special preshaped lead shells are foreseen. The required shape of the lead is obtained by extrusion of profiles as shown in figures 1 and 2. For reasons of transport and handling, the length is limited to about 3 m. The inner surface of the lead profiles is coated with a thin tin layer during or

Figure 5: The fraction of primary radiation scattered and subsequently incident per metre of vacuum chamber as a function of the distance from the point of impact for 0.1, 0.4 and 1.4 MeV primary photons.

Figure 6: 12m long hydraulic press for lead cladding.

immediately after the extrusion. For heating of the 12 m long vacuum chambers advantage of the cooling channels has been taken by circulating hot oil at 210°C. A convenient way of obtaining the external pressure during the cladding consists in putting the whole chamber into a temperature resistant silicone rubber bag which is evacuated. Higher pressures may be obtained with the hydraulic press shown in figure 6 which can accommodate vacuum chambers up to 12 m length.

Alternative methods

Several alternative methods of lead cladding have been investigated and were later abandoned for technical reasons. Extrusion of the lead shield around the aluminium profile cannot be applied to the finished vacuum chambers because of the presence of the end flanges and the lateral pump ports. Excessive temperature and deformation of the chamber during cooldown cannot be avoided when using the method of casting lead. Spraying the lead directly onto the vacuum chamber has been abandoned for economic and safety reasons.

Future requirements

The lead coating process has been tested on full scale vacuum chambers of up to 12 m length and shown to give good results. A series production rate in excess of 3 chambers per day may be obtained. Possibilities of optimising the cladding process while remaining compatible with the vacuum chamber manufacture and production rate are under study. A non-destructive method for testing the quality of the lead bonding on the finished chambers has been evaluated by observing the ultrasonic echo from the lead-aluminium interface.

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